Radiographic Imaging with Cosmic Ray Muons[1-4]

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Abstract The threat of the detonation of a nuclear device in a major US city has prompted research aimed at providing more robust border surveillance for contraband nuclear material. The small amount of material needed to construct a nuclear device and the ease with which neutron and gamma ray signatures can be obscured with shielding makes this job difficult. We demonstrate a new technique which uses multiple scattering of cosmic ray muons to selectively detect high-z material in a background of normal cargo. The advantages of this technique are that it is passive, does not deliver any radiation dose above background, and is selective to high-z dense materials. The research that has lead to the development of this new radiography will be reviewed, and future extensions will be summarized

1.Schultz LJ, et al. *Nuclear Instruments & Methods in Physics Research Section A-Accelerators Spectrometers Detectors and Associated Equipment* 519: 687 (2004)
2.Priedhorsky WC, et al. *Review of Scientific Instruments* 74: 4294 (2003)
3.Schult LJ, et al. *International Meeting on Nuclear Applications of Accelerator Technology: Accelerator Application in a Nuclear Renaissance*: 238 (2003)
4.Borozdin KN, et al. *Scattering muon radiography and its application to the detection of high-Z materials*. Presented at 2003 IEEE Nuclear Science Symposium. Conference Record, 19-25 Oct. 2003, Portland, OR, USA (2003)

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Physics

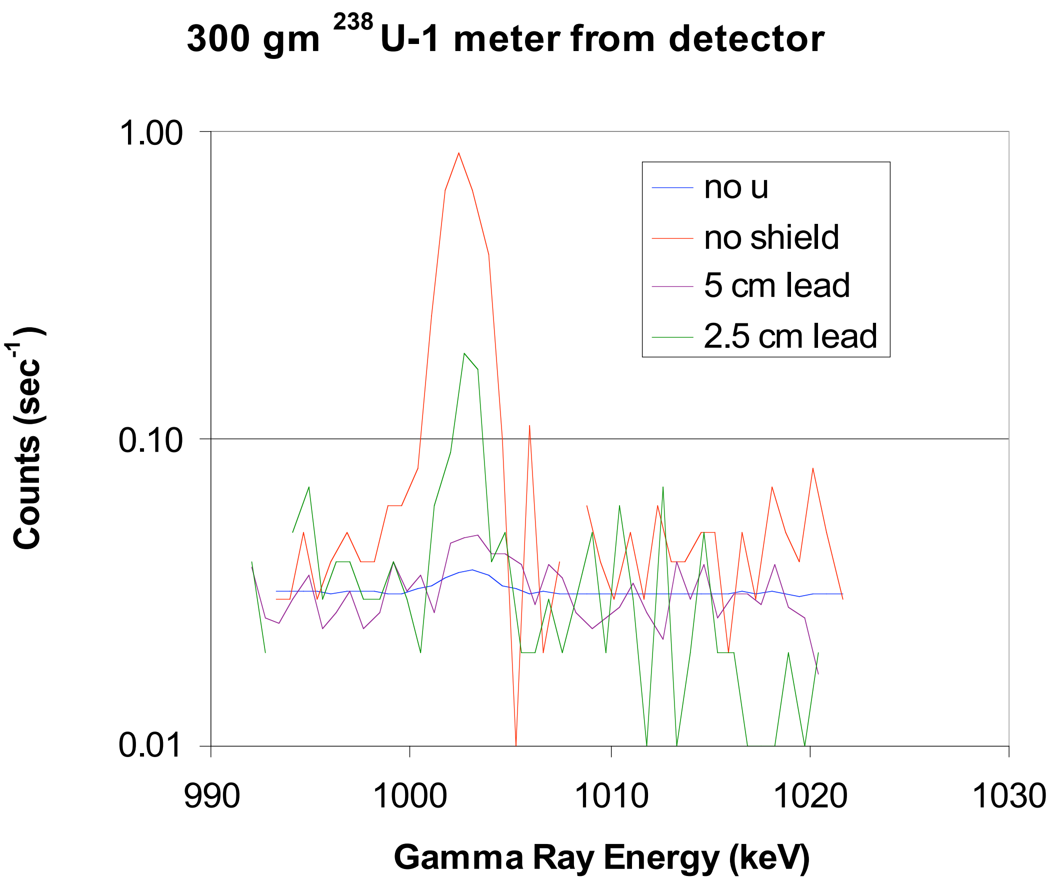
The problem: surreptitious transport of special nuclear material

The breakup of the Soviet Union left nuclear materials scattered throughout the newly independent states and increased the potential for the theft of those materials, and for organized criminals to enter the smuggling business. As horrible as the tragedies in Oklahoma City and the World Trade Center were, imagine the destruction that could have resulted had there been a small-scale nuclear device explode there."—**President William Jefferson Clinton**

"Some possibilities for moving this type of material are:
1)-superimpose the shipment of small, well-shielded packages on established drug and contraband routes.
2)-Ship materials conventionally in well shielded, small containers through a surreptitiously network of widely dispersed handlers.
3)-man carry many small quantities across the mostly porous borders of the United States.
4)-Use diversified distribution techniques (routes and conveyances) by requiring multiple way-points and altering the characteristics of external shipping containers at each point.
5)-Mix materials and legitimate products for routine deliveries.
The formidable nature of the tasks required to detect and identify well packaged fissile materials in small quantities highly questionable." —**Gene R. Kelley, "A Terrorist Threat-The movement of Black Market Nuclear Materials into the United States", November 2001**.

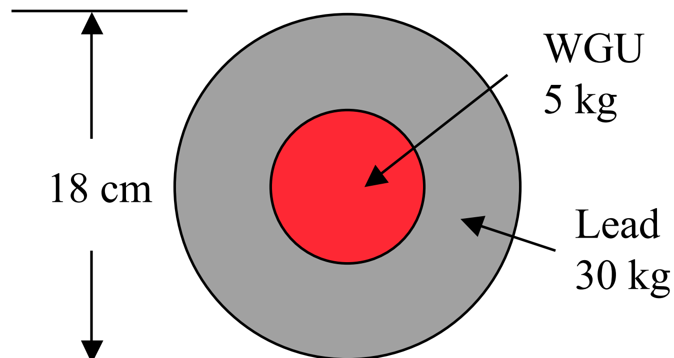
Conventional Technologies: High resolution γ-ray counting

Nuclear material is radioactive:
Weapon grade uranium (WGU): 10% ^{238}U 90% ^{235}U



- Unshielded Kg quantities of highly enriched uranium can be detected with high reliability with 1 minute counting times by detecting γ's from the ^{238}U impurity.
- Shielding threat object requires ~5 cm of lead, gold, tungsten, or other high-z material

Small well shielded package



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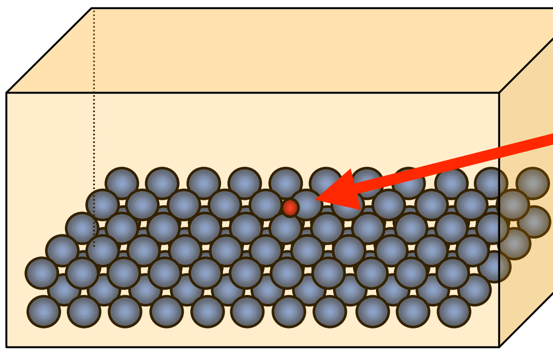
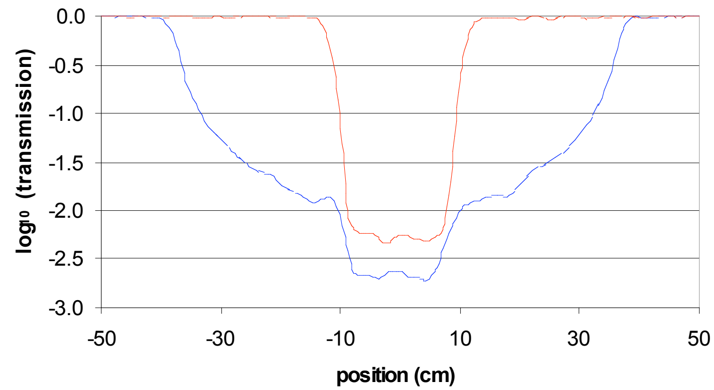
Conventional Technologies: why is there a problem; Mega-Volt x-radiography

Uranium among automobile differentials



20 kg Uranium Sphere 12 cm dia



Expect transmission to be 5.5×10^{-5}

Fan beam 8 MV simulation

Uranium ball

- X-rays can visualize objects, even in some dense, cluttered cargo.
- Definitive signatures of high z objects are confused by scatter backgrounds.
- Transmission insufficient for many cargos

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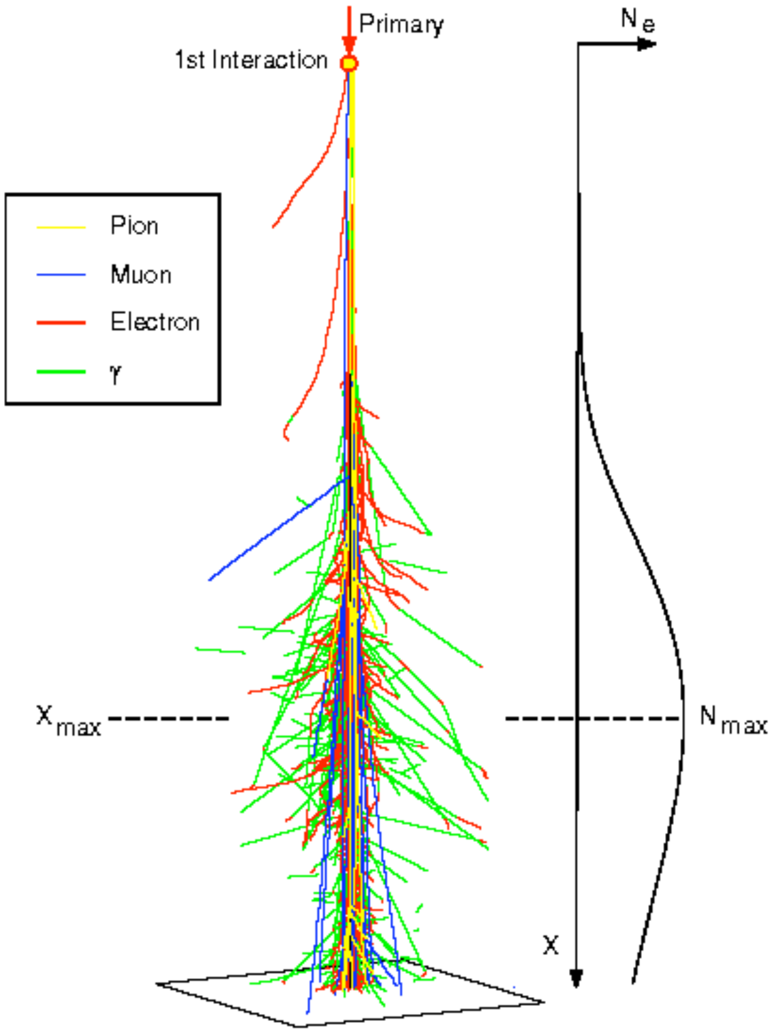
Cosmic ray muons are ubiquitous



- As cosmic rays strike our upper atmosphere, they interact, producing many particles including pions (τ=26 ns)(hadron) which decay into muons (τ=2.2 μsec) (lepton)

- Muons interact only through the Coulomb and weak force and thus have a large penetrating ability and are able to go through tens of meters of rock with low absorption.

- Muons arrive at a rate of 10,000 per square meter per minute (1/cm^2/minute).

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Muon interactions with matter

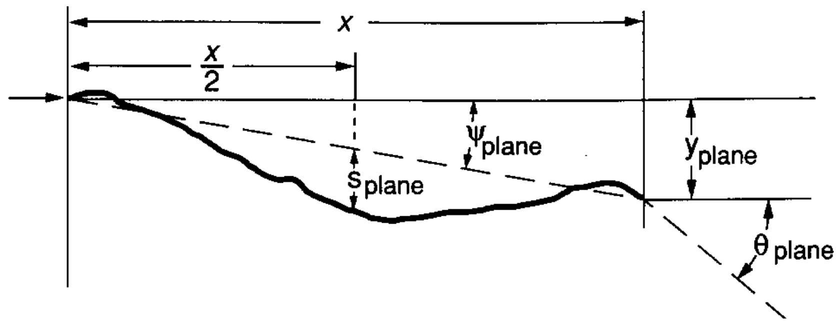

Fig. 4.3. Cloud chamber tracks of α particles, showing delta rays (collisions with atomic electrons, which are sufficiently violent to create secondary ionization). In the right picture, large changes of direction due to nuclear collisions are visible [T. Alper, Z. Physik 67 (1932) 172].

- **Energy loss[1]**
  - **Most sensitive but expensive**
- **Range[1,*]**
  - **Useful for archeological and geological**
- **Multiple scattering[2-4]**
  - **Cost effective and simple**

1. Livingston MS, Bethe HA. *Rev. Mod. Phys.* 9: 245 (1937)
2. Rossi B. *High-Energy Particles*. New Jersey: Prentice-Hall (1952)
3. Bethe HA. *Physical Review* 89: 1256 (1953)
4. Moliere G. *Zeitschrift fur Naturforschung Section A-A Journal of Physical Sciences* 2: 133 (1947)

*See talks by:
Arturo Menchaca Rocha
Kanetada Nagamine

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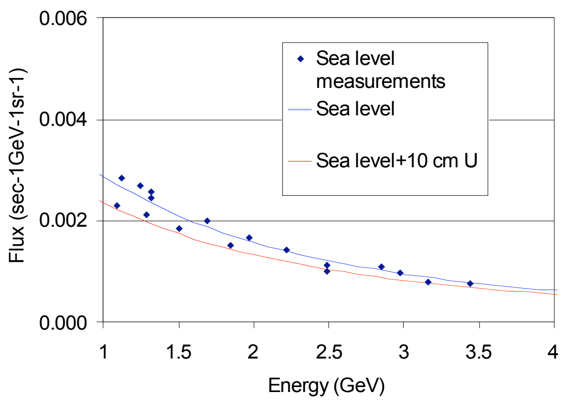
Muon Radiography

How well can a 1000 cm^3 volume of uranium be measured in 1 minute

Range*



$$\Delta l = \frac{\lambda}{\sqrt{N}}$$

$$\lambda \approx 120\,\text{cm}$$

$$\frac{\Delta l}{l} \approx 1.2$$

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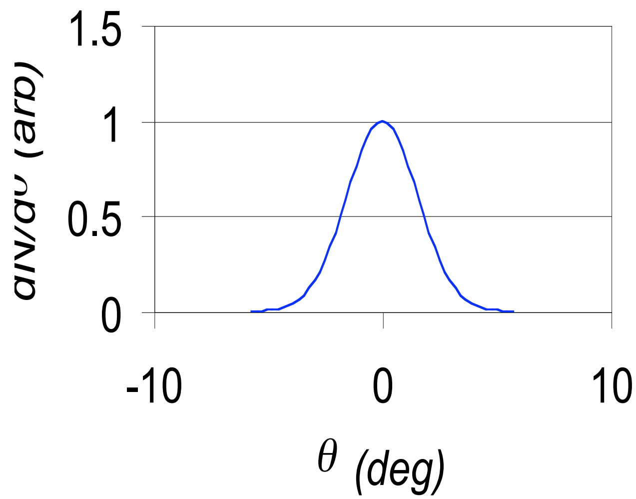
Arturo Menchaca Rocha
Kanetada Nagamine

Multiple scattering

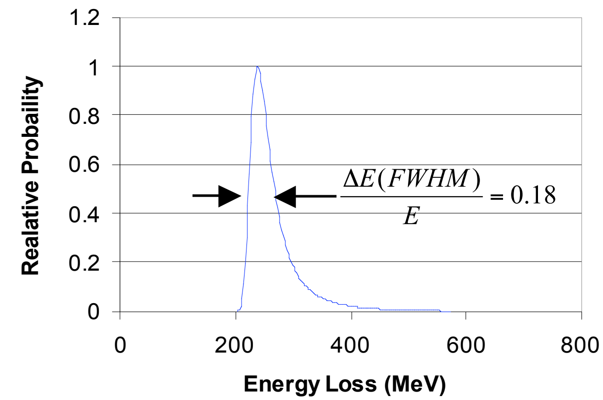


$$\Delta l = \frac{l}{\sqrt{N}}$$

$$l = 10\,\text{cm}$$

$$\frac{\text{Ä}l}{l} = 0.1$$

Energy Loss



$$\Delta l = \frac{0.08 \times l}{\sqrt{N}}$$

$$l = 10\,\text{cm}$$

$$\frac{\text{Ä}l}{l} = 0.008$$

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Cosmic ray muons can provide information with only background dose

Use tomography to localize scattering

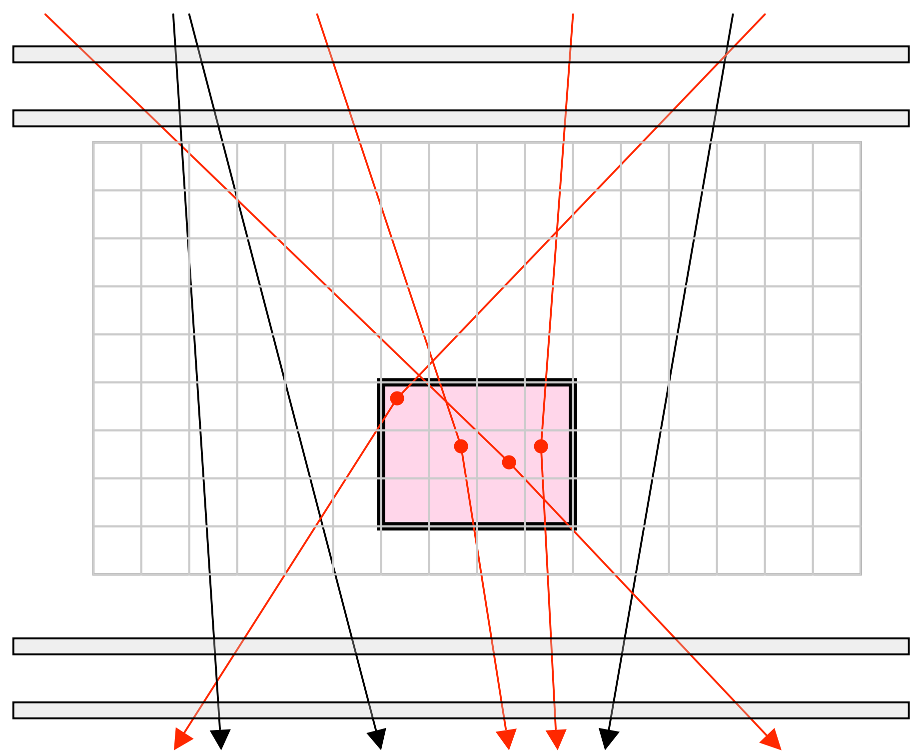
$$\Delta x = \theta_{RMS} L$$
$$= 0.02 \times 200 cm$$
$$= 4 cm$$

Poisson statistics determine the sensitivity

$$\frac{\Delta\theta}{\theta} = \frac{1}{\sqrt{2N}}$$
$$N = 100/\min$$
$$\Delta\theta = 0.07\theta \text{ after 1 minute of counting}$$

One minute of counting distinguishes a 10 cm cube of iron from a 10 cm cube of lead at 6 std deviations

Material	dE/dx	χ
	MeV-cm^2/gm	cm
H_2O	2.06	36
Fe	1.87	1.76
Pb	1.54	0.56



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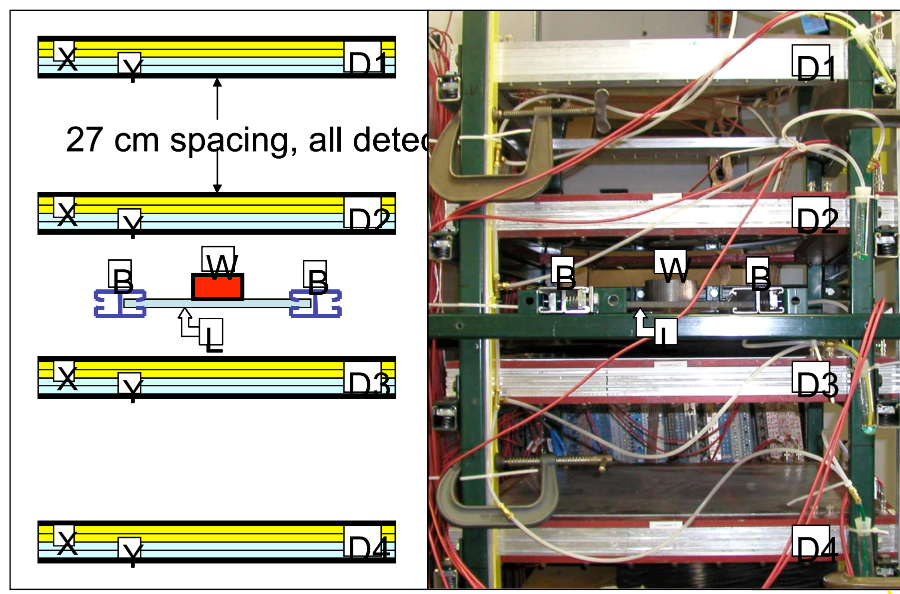
Monte Carlo Simulation

Experiment

Simulation

- Cosmic ray muon generator / multiple scattering simulation.
- Good agreement with experiment.
- Allows for extrapolation to larger, more complex scenes.



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Momentum determination

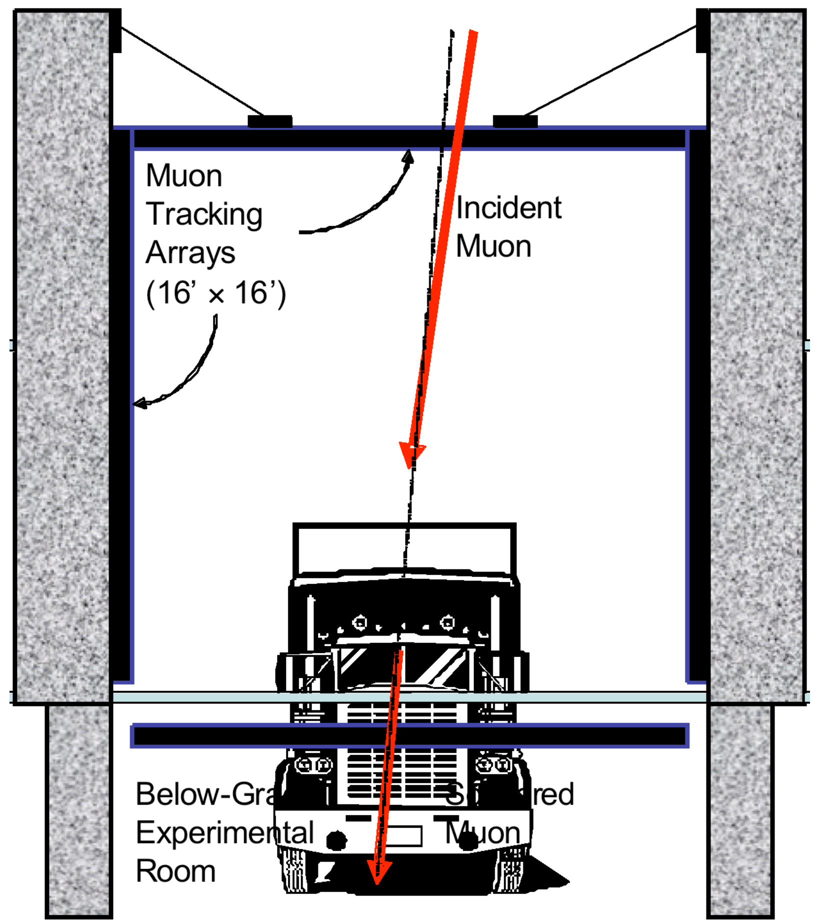
$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

$$\theta_0 = \frac{13.5}{p\beta}\sqrt{\frac{l}{\chi}}$$

$$p = \frac{13.5}{\theta_0\,\beta}\sqrt{\frac{l}{\chi}}$$

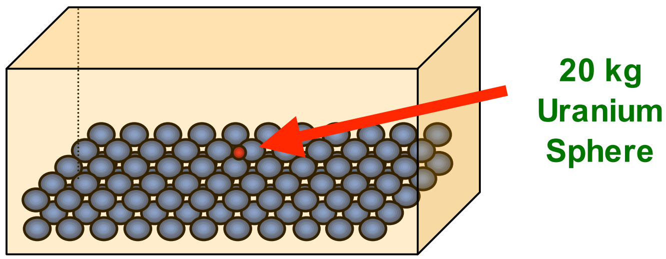
$$\frac{\Delta p}{p} \approx \frac{1}{\sqrt{2\mathrm{n}}}$$

Measure muon momentum by using track residuals in the incident and exit detector planes

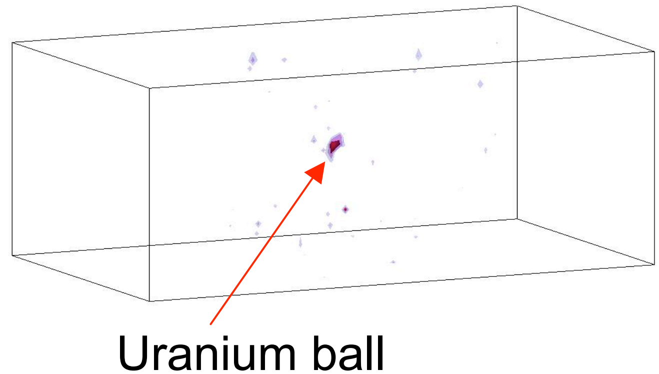


Monte Carlo studies of car and container radiography*

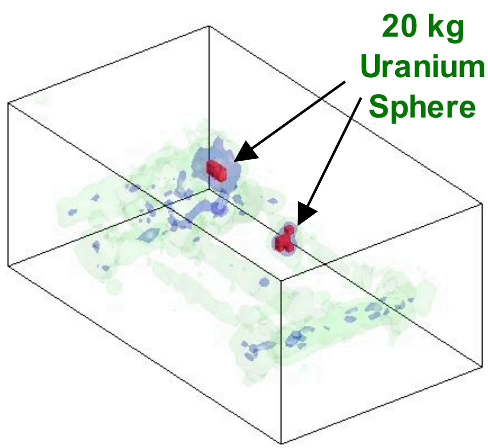
Uranium in a cargo of automobile differentials



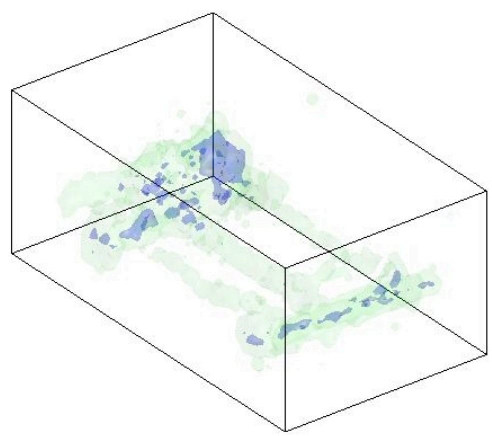
60 second exposure
Ray-crossing algorithm



Automobile with threat objects



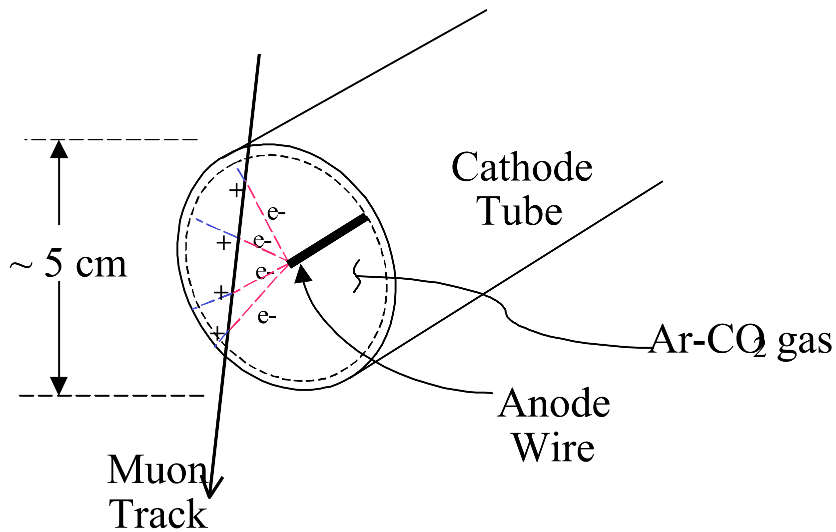
without threat objects

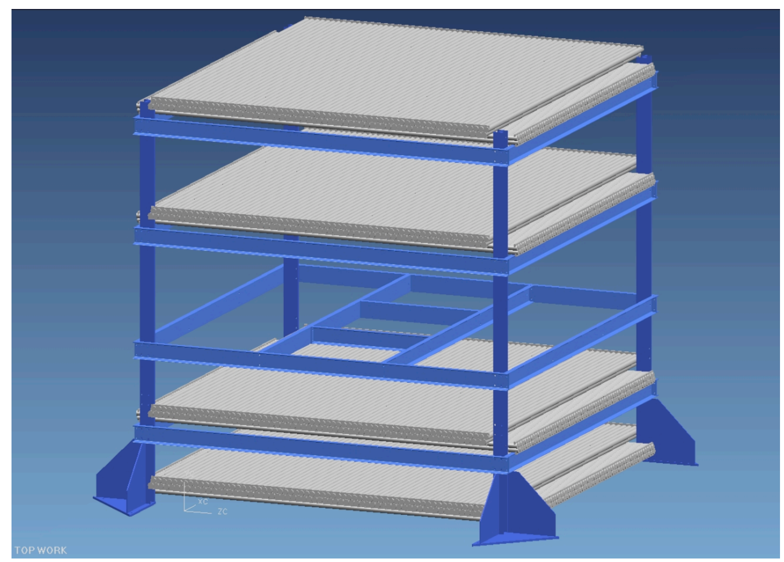


*Details in talk by Rich Chartrand

Prototype apparatus

- **99% efficiency**
- **18-100 ^{o}C**
- **2 weeks with no gas flow**





Conclusion

- The illicit transport of nuclear material can be controlled using techniques from nuclear and particle physics.